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TELEMETRY CASE REPORT

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Best practice for collar deployment of tri-axial accelerometers on a terrestrial quadruped to provide accurate measurement of body acceleration

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Abstract

Background: Tri-axial accelerometers are frequently deployed on terrestrial quadrupedal mammals using collars, because they are easy to fit and are thought to have minimal impact on the subject. Collar-attached devices are not fixed to the body and can move independently of the body. This may result in inaccurate measures of acceleration, reducing the accuracy of measured body movement. We determined the effect of collar size and collar weight on acceleration measured by a collar-mounted accelerometer on a quadruped mammal. The aim was to suggest best practice for sizes and weights of collars on which to deploy tri-axial accelerometers. Using pygmy goats, *Capra aegagrus hircus*, which were trained to walk at different speeds (0.8–3.0 km/h) on a treadmill, we measured body acceleration using a collar-mounted tri-axial accelerometer, with different collar sizes (individual neck circumference + 1 cm to + 9 cm) and collar weight (0.4% to 1.2% of individual weight).

Results: There was a significant effect of collar size, collar weight and walking speed on measured acceleration. Measured acceleration was less accurate and more variable when collars were looser and heavier. To measure body acceleration more accurately, we found that collar size should be within 5 cm or 16% of an individual's neck circumference when it was heavy (up to 1.2% of animal's body weight) or within 7 cm (33%) of neck circumference if the collar was light (up to 0.6% of animal body weight).

Conclusion: We suggest that not only reporting collar size and weight for welfare purposes, but it is also important to consider these aspects for scientific rigour, to ensure data are collected as accurately as possible. We provide guidelines for researchers fitting collar-attached devices to ensure a higher degree of accuracy of recorded body acceleration.

Keywords: Tri-axial accelerometry, Terrestrial mammal, Collar-attached, Collar size, Collar weight, Pygmy goat

Introduction

Advances in logging technology have led to the increased use of animal-borne tri-axial accelerometers to study domesticated and free-living animals [1–3]. This

technology enables detailed information to be recorded about an individual's orientation and body movement [4]. Devices typically record acceleration data at high frequencies (e.g. 20–50 Hz) in three axes which enables dynamic body acceleration to be calculated, such as vectorial dynamic body acceleration (VeDBA) [5, 6]. Measured acceleration can be used to identify patterns of behaviour through analyses of body movement and orientation [7–10]. Body acceleration has also been shown

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to correlate with oxygen consumption, and along with other movement-related metrics, can be used as an index of energy expenditure [11–13]. Furthermore, it can be included with other recorded data such as magnetic compass heading to infer movement paths of individuals by dead-reckoning [14].

The importance of correct attachment and positioning of biologging devices is broadly accepted, both for animal welfare considerations [15–17] and application purposes such as tag position to answer specific movement-related questions [5, 18]. Generally, devices are attached to the subject's body, as close to the centre of mass as possible, and aligned so that the direction of measured axes is aligned with the organism's anatomical axes [19]. Such measures are easier to apply when attaching devices directly to the animal's hair or feathers using tape or glue, as is the case, for example, when attaching logging devices to marine mammals [20–22]. However, many studies utilise collar-attached systems, most commonly for deployment on quadrupedal terrestrial mammals [8, 23]. This moves the device away from the centre of mass, and unlike directly attached devices, collar-attached devices are not fixed to the body and may therefore move independently to the subject [19]. This may result in less accurate measurements of acceleration of the animal, and reduce the ability of accelerometry to determine behavioural patterns and body orientation.

Previous studies have proposed that in the interests of animal welfare, collar weight should not exceed 2% of body weight and collar size should be of appropriate tightness, dependent on the study species [17, 24]. A few studies have evaluated the effect of collar weight on the subjects' behaviour [17, 25] and investigated the welfare consequences of collar tightness [26]. However, the effect of collar size and weight on acceleration measured by a collar-attached device has not yet been quantified. These determinations are important because device weight is

related to battery size and, therefore, to the period over which a device can record. Researchers may only have one opportunity to deploy a device, and thus, it is important to ensure that collar size and weight are optimal for accurate measurement of body acceleration.

We used African pygmy goats (*Capra aegagrus hircus*) as a model quadruped species to measure body acceleration of walking, measured via VeDBA over a second, at different speeds on a treadmill, which acted as a controlled environment. The main aims of this study were (1) to assess the effect of different collar sizes, ranging from 3 to 10 cm larger than the subjects' neck circumferences (S1–S5), and weights, ranging from 0.4 to 1.2% of the subjects' body weights (W1–W5), on the measured acceleration of a collar-mounted device (Table 1); (2) to investigate the acceleration of a device acting as a control, positioned on the body of the animal using a harness so that the device is not subject to collar roll; and (3) to assess the effect of collar sizes and weights on the difference between acceleration measured on the collar and the harness. Selection amongst candidate general linear models (GLMs) used an information theoretic approach based on Akaike's Information Criteria (corrected for small sample size) (AIC_c) [27]. Using predictions from the GLM output, we developed guidelines for relative collar sizes and weights, in order for future studies to measure body acceleration as accurately as possible.

Results

Effect of collar size and weight on VeDBA

The interaction between collar size and weight was retained in the model, positively affecting mean VeDBA ($\Delta AIC = 110.7$ relative to the best model that excluded the interaction) with higher mean values and more variation recorded on looser and heavier collars (Fig. 1; Additional file 1). For heavy and looser collars (S5, W5), VeDBA was predicted to increase twice as fast as that for

Table 1 Each measured combination of collar size (S1–S5), ranging from 1 to 9 cm greater than the animals' neck circumferences, and collar weight (W1–W5), ranging from 0.4 to 1.2% of the animals' masses, for the different goats (G01–G04)

Collar sizes	Collar weights				
	W1 (0.4% weight)	W2 (0.6% weight)	W3 (0.8% weight)	W4 (1.0% weight)	W5 (1.2% weight)
S1 (neck size + 3% or + 1 cm)	G01, G02	All	All	All	All
S2 (neck size + 10% or + 3 cm)	G01, G02	G03, G04	–	–	All
S3 (neck size + 16% or + 5 cm)	G01, G02	G03, G04	–	–	All
S4 (neck size + 23% or + 7 cm)	G01, G02	G03, G04	–	–	All
S5 (neck size + 30% or + 9 cm)	G01, G02	All	All	All	All

All collar sizes were measured with the smallest and largest collar weight, and all collar weights were measured with the smallest and largest collar size, dashes represent collar combinations that were not measured due to study design. 0.4% of weight (W1) was not measured for goats G03 and G04 because the minimum weight of the collar was larger than 0.3% of body weight

tighter and lighter collars (S1, W1 and W2). When the collar was loose but light (S5, W1 and W2), VeDBA was predicted to increase by more than two-thirds than if the collar was tight but heavy (S1, W5).

Collar parameters had an important effect on the relationship between VeDBA and animal travel speed (Fig. 2; Table 2; Additional file 1). There was a positive relationship between speed and mean VeDBA recorded from the collar-attached device. There were also positive interactions between collar size and speed and collar weight and speed retained in the model. There was no interaction between speed and goat ID; however, goat ID was retained in the model.

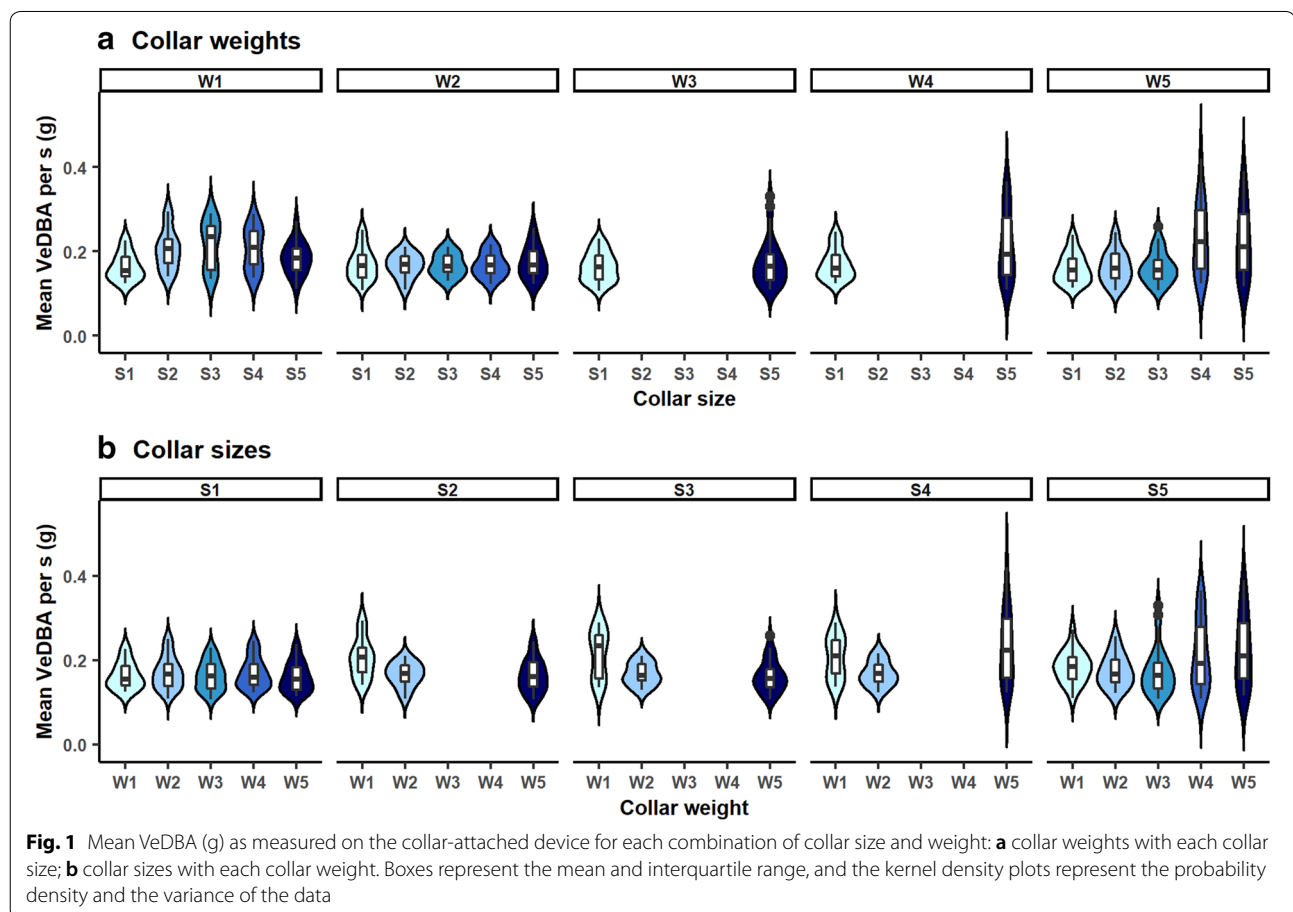
VeDBA measured by the harness

We investigated the relationship of harness-measured acceleration with the other variables to confirm that the relationship between acceleration and speed measured on the harness did not vary with different collar weights or sizes. There was a positive relationship between speed and VeDBA measured using the harness-attached device ($\Delta\text{AIC}=578.6$ relative to the best model that excluded the interaction; Table 2) and goat ID was retained in the

model. The effects of collar size and weight were retained. However, the interactions between speed and collar weight, or speed and collar size were not retained in the model ($\Delta\text{AIC}=3.3$ and $\Delta\text{AIC}=1.1$, respectively, relative to the best model that excluded the interaction). Showing that despite retaining collar size and weight in the model, it did not influence the relationship between acceleration and speed.

Difference between collar and harness

The interaction between collar size and collar weight was retained in the model, positively affecting difVeDBA (the difference between collar- and harness-measured acceleration), with a larger difference and more variation recorded when the collar was looser and heavier ($\Delta\text{AIC}=8.99$ relative to the best model that excluded the interaction; Table 2; Fig. 3). When collar size increased, the predicted increase in difVeDBA (g) per km/h was up to four times greater for heavier collars than for lighter collars, and when collar weight increased, the predicted increase was up to three times larger for looser collars than tighter collars (Table 3; Additional file 1).



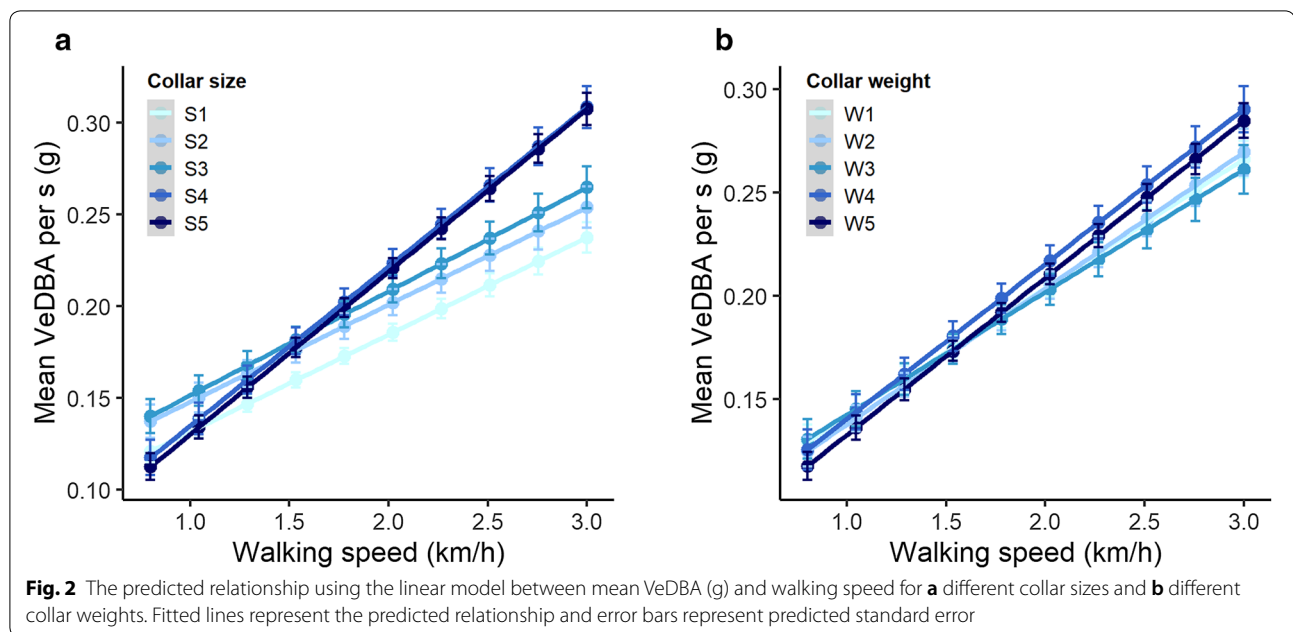


Table 2 The effect of collar size and weight on measured VeDBA, including the relationship between speed and goat ID as a fixed factor

Candidate models and variables retained	df	logLik	AIC _c	ΔAIC	Weight
1. Effect of collar size and weight on VeDBA					
<i>CS*CW+CS*Sp+CW*Sp+Gt</i>	32	1105.9	−2142.7	0.00	0.522
CS*CW+CS*Sp+CW*Sp+Gt*Sp	35	1109.4	−2142.5	0.18	0.477
2. VeDBA measured by the harness					
<i>CS+CW+Gt+Sp</i>	14	977.59	−1926.2	0.00	0.437
CS*Sp+CW+Gt	18	981.38	−1925.1	1.06	0.257
CS*Sp+CW+Gt	22	984.92	−1923.4	2.79	0.108
CS*Sp+CW*Sp+Gt	18	980.25	−1922.9	3.33	0.083
CS+CW+Gt*Sp	17	978.64	−1921.8	4.36	0.049
CS*Sp+CW+Gt*Sp	21	982.69	−1921.2	5.03	0.035
3. Difference between collar and harness					
<i>CS*CW+CS*Sp+CW*Sp+Gt*Sp</i>	35	1092.1	−2108.0	0.00	0.969

Summaries of selected models for each with the AIC-best model are shown in *italic*. The fixed variables included in each model are collar size (CS), collar weight (CW), speed (Sp) and goat ID (Gt)

The extent of agreement between collar- and harness-derived estimates of VeDBA was negatively affected by animal travel speed as difVeDBA increased with speed ($\Delta AIC = 260.1$ relative to the best model that excluded the interaction). There were significant interactions between speed and collar size (Fig. 3a) and speed and collar weight (Fig. 3b) on measured VeDBA. There was also a significant interaction between goat ID and speed.

Discussion

Our results indicate that the size and weight of a collar are likely to affect acceleration measured in animal-borne tags. To ensure ethical deployment of collars onto subject animals, researchers must demonstrate that the best available techniques are being used that do not cause harm [16]. Therefore, in the context of animal welfare, it is also important to consider the effect of collar size and weight on the ability to measure the subject's body movement accurately.

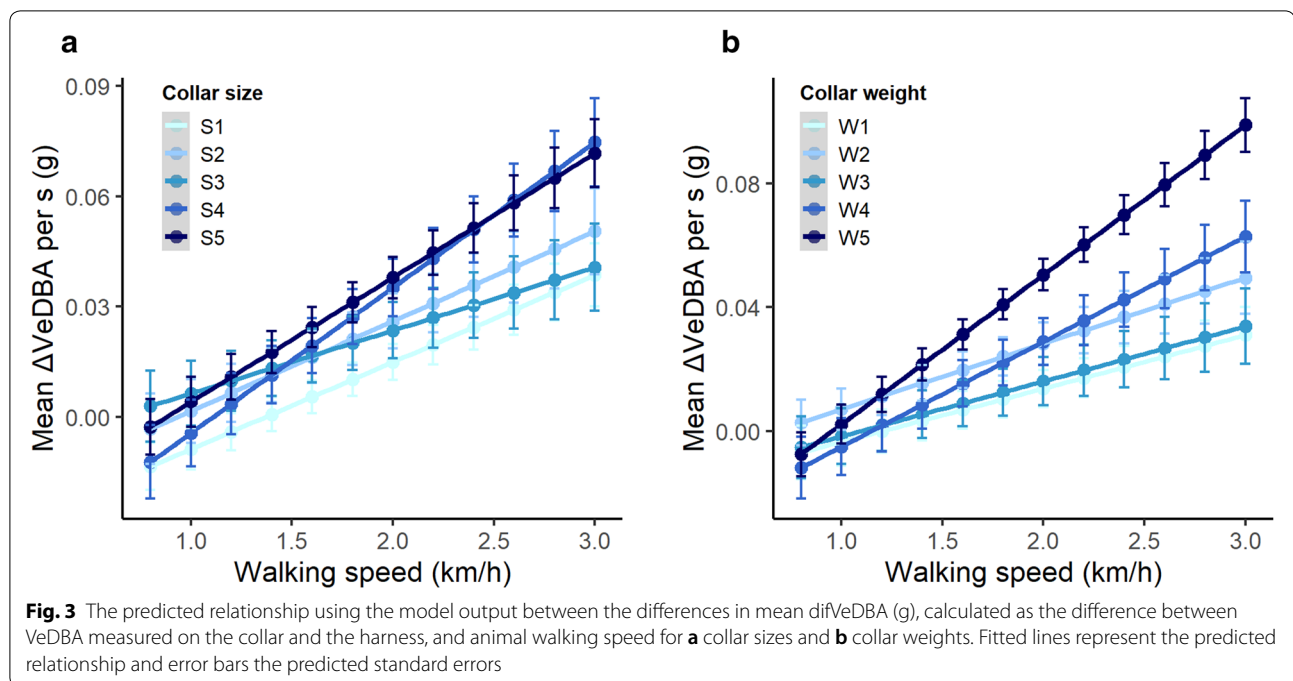


Table 3 Predicted measured increase difVeDBA (g) per km/h for each collar size (S1–S5) and weight (W1–W5) combination with predicted standard error

Collar size	Collar weight				
	W1	W2	W3	W4	W5
S1	0.013 ± 0.007 ^a	0.017 ± 0.005 ^a	0.014 ± 0.06 ^a	0.030 ± 0.005 ^b	0.044 ± 0.006 ^c
S2	0.014 ± 0.007 ^a	0.018 ± 0.008 ^a	0.015 ± 0.01 ^a	0.031 ± 0.01 ^b	0.045 ± 0.006 ^c
S3	0.010 ± 0.008 ^a	0.011 ± 0.008 ^a	0.010 ± 0.01 ^a	0.023 ± 0.01 ^b	0.038 ± 0.006 ^c
S4	0.029 ± 0.007 ^b	0.033 ± 0.009 ^b	0.030 ± 0.01 ^b	0.046 ± 0.01 ^c	0.060 ± 0.007 ^d
S5	0.023 ± 0.007 ^b	0.027 ± 0.008 ^b	0.024 ± 0.006 ^b	0.040 ± 0.006 ^c	0.054 ± 0.007 ^d

The size of the difference between values which represents the effect size of each combination is indicated; < 0.02^a, > 0.02 and < 0.035^b, > 0.035 and < 0.05^c, > 0.05^d

Collars that are too tight may cause discomfort or injury and not account for potential animal growth, whilst collars that are too loose may ensnare the animal or be prematurely removed [28]. In line with ethical recommendations, we did not test collar sizes that are predicted to cause the animal discomfort [15]. Our results show, however, that the size and weight of the collar have a significant effect on the measured acceleration when the subject is walking. Tighter and lighter collars are more likely to provide more accurate measures of body movement, with smaller differences in effect size and variation between collar sizes S1 to S3 and collar weights W1 to W3. These collar parameters are also more likely to fit with ethical constraints. In contrast, looser and heavier collars are more likely to yield larger acceleration values and variation, reducing accuracy of measured

acceleration. Collar sizes S4 and S5 with collar weight W5 were likely to have an effect size five times larger than the collar combinations S1/2 and W1/2.

This study also measured the interaction between collar size and weight. We found that if the collar is fitted tightly (neck + 5 cm or 16% of neck circumference), collar weight will have minimal effects on measured acceleration, see Table 2. As the increase in VeDBA is larger for heavier collars, it is recommended that when deploying collars heavier than 0.8% of body weight, collar size should be kept to within 5 cm or 16% of the subject's neck size. If the collar is looser (> neck + 5 cm), then weight will have a larger effect; therefore, if this size is used, researchers should consider using collars within 0.6% of the subject's body weight. The fact that the effect of collar size was smaller than that of weight demonstrates that

size is important to consider but, within 16% of neck circumference, is less likely to affect measured acceleration significantly. Changes in body mass must be considered when deploying collars, as many ungulates undergo substantial body mass changes seasonally, affecting collar tightness with the potential to cause harm to the subject [26, 29]. Therefore, collars should be deployed that are neither too tight nor too loose in proportion to the neck size of the subject to satisfy ethics and provide accurate measurement of relative body acceleration. Of course, this study does not address body mass changes; considerations in relation to this must be made for any given study species.

This study measured the effect of collar weight within 1.2% of the subject's body weight. The commonly suggested '5% (or 3%) rule' has been suggested to be arbitrary [24]. However, studies investigating the effect of logger weight have mainly focused on flying animals [30, 31]. On terrestrial mammals, it has been suggested that 2% is more appropriate for collar-attached devices [15], and even an increase from 0.4 to 0.6% in collar weight has been shown to affect the behaviour of a large ungulate [25]. This study shows that when using collar-attached devices to measure body movement, weight has an effect on measured acceleration. It is important to consider device weight for both measurement accuracy as well as considering its potential influence on behaviour.

The effect of collar size and weight also varied with walking speed: at low speeds, there was little variation between collar sizes and weights, but at higher speeds, variation increased [19]. Wild animals are likely to display a wider range of behaviours and larger accelerations than in our controlled experimental setting, depending on the species' body size and characteristics of their body movement [10, 23]. The larger variation in these behaviours may be exaggerated by collars that are loose and/or heavy; therefore, in a normal setting, the observed effects of collar size and weight might be larger and more variable. It is, therefore, important to consider that this effect may be different in behaviours other than walking. Furthermore, when applying these recommendations to other species, it is important to consider other factors such as body shape and differences in movement, making deployment decisions based on the study species in question.

Conclusions

This study highlights that both the size and weight of the collar affect measured body acceleration in a quadrupedal terrestrial mammal. The importance of correctly fitting a collar for deployment of devices that record body movement, to ensure the highest standards of both welfare and scientific precision, is highlighted. We recommend that

collar tightness be kept to +16% of neck size and collar weight to be kept within 0.8% of the subjects' body mass. If the collar is tighter than this +16% guideline, collar weight will have less effect, and thus, heavier collars will not have a negative effect. We suggest consideration of these recommendations when deploying collar-mounted devices and that researchers should report the size and weight in research outputs to demonstrate best practise and enable similar studies to employ comparable and reproducible methods.

Methods

Study animals

The study took place in June 2018 at Belfast zoo, within the subjects' normal housing area. Four female adult African pygmy goats were used (body weight: 13.5–23.1 kg; Table 4), as they are easily trained domesticated caprids amenable to the use of collars and harnesses. Using positive reinforcement, consisting of the subject's normal daily food, individuals were trained to walk on a treadmill. Individuals were habituated to the equipment and then trained in stages over a period of 1 month. Each individual walked on a treadmill for a period of up to 10 min, at different speeds, wearing both a collar (Dog collar, Pets at Home, UK; 53 g) and a harness (Adjustable nylon dog harness, Bunty Pet Products, UK; 128 g).

Acceleration data collection

We used tri-axial accelerometers (Daily Diary tag, Wildbyte Technologies; [19]) that measured acceleration in three orthogonal axes at a sampling rate of 40 Hz. The devices were powered by a Li-Po rechargeable battery (Cameron Sino, HK, 31.54 × 25.13 × 3.95 mm; 5.5 g), enclosed in plastic casing (35 × 45 × 12 mm; combined mass 15.2 g) and attached using waterproof tape (Tesa® tape 4651, Tesa, Germany). One accelerometer was placed on the collar in the ventral position on the subject's neck (Fig. 4); using different combinations of collar sizes, from approximately 3 to 30% (+1 to +9 cm) larger than individuals' neck sizes, and weights, from 0.4 to 1.2% (88 to 285 g) of individuals' body masses (Table 4). Weight was added adjacent to the accelerometer using metal nuts taped to the collar, with the aim

Table 4 Details of each individual goat (G01–G04) used in the study, including body weight, neck size and age

Individual	Body weight (kg)	Neck size (cm)	Age
G01	23.1	34	8
G02	22.5	32	5
G03	15.2	29	3
G04	13.5	26	3

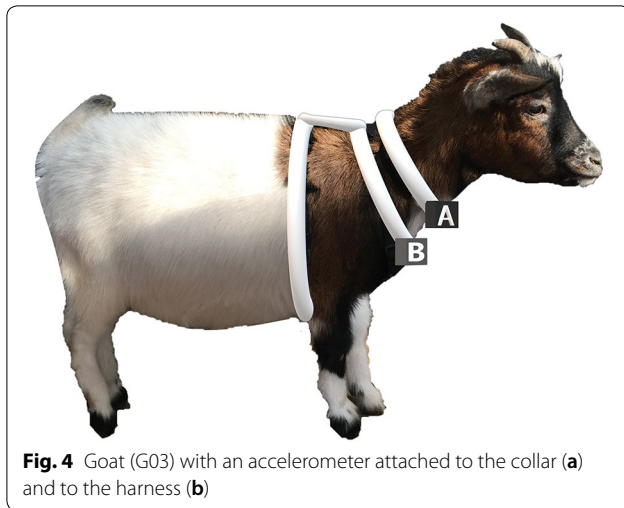


Fig. 4 Goat (G03) with an accelerometer attached to the collar (a) and to the harness (b)

of resembling larger battery weight. A second accelerometer was placed on the harness in a ventral position, to act as a control in the same position as the first device. The harness provided a more rigid placement, minimising movement of the accelerometer beyond that of the study animal (Fig. 4). Collar combinations measured were each collar size with the smallest and largest weight, and each collar weight with the tightest and loosest collar (Table 1). After each individual was trained and acclimated to the equipment, each collar combination was tested on each individual once. Collar combinations that tested the largest and smallest collar size with the lightest and heaviest collar weight were measured. Goats walked at speeds between 0.8 and 3.0 km/h at increments of 0.2 km/h and walking speeds were recorded in a random order, for a minimum duration of 1 min. Each individual was video-recorded during data collection to remove data obtained during behaviours other than walking (Fujifilm XP120, Fujifilm, Japan; 59.94 frame/s). Sections, where the speed of the treadmill was changing (~ 15 s), were also removed.

Data were processed and analysed in R version 3.6.2 [32]. Data were labelled for the corresponding speed, collar size and collar weight. To calculate VeDBA, raw acceleration for each axis was used to derive static acceleration over a running mean of 2 s and thus the vectoral sum of dynamic body acceleration was calculated (VeDBA) [33]. Mean VeDBA measured over a 1 s interval was calculated for the collar- and harness-attached devices. To determine how acceleration measured by the collar changes, the difference between the collar and harness attached devices was also calculated ($\text{difVeDBA} = \text{VeDBA}_{\text{collar}} - \text{VeDBA}_{\text{harness}}$).

Data analysis

To understand the relationship between collar size and weight on measured acceleration (VeDBA), three separate general linear fixed effect models were used to (1) investigate the VeDBA measured on the collar-attached device; (2) investigate the VeDBA measured on the harness-attached device; and (3) investigate the relationship with the difference in VeDBA measured from the two devices (difVeDBA). The fixed variables included in the models were goat ID, walking speed and collar size and weight as categorical variables. A two-way interaction between collar size and weight was included. The two-way interactions between speed and the variables, goat ID, collar size and collar weight, were also included. The global models were simplified using the “dredge” function in the R package MuMin [34] which uses AIC_c to assess the best fit model [27]. Models within $\Delta\text{AIC}_c \leq 6$ were retained for inference and the simplest model was selected (Table 2 and Additional file 1) [35]. Model residuals were checked for a normal distribution.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s40317-020-00198-9>.

Additional file 1. The estimated coefficients of variables for each general linear model used: (1) effect of collar size and weight on VeDBA, (2) VeDBA measured by the harness and (3) difference between collar and harness. Bold font indicates that 95% confidence intervals for coefficients did not overlap zero.

Abbreviations

VeDBA: Vectoral Dynamic Body Acceleration; difVeDBA: Difference of VeDBA measured on collar and harness; GLM: General Linear Model; AIC_c : Akaike Information Criteria.

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Authors' contributions

ED, RPW and DMS conceived the study design. ED collected the data. ED and PS analysed the data. ED drafted the manuscript. All authors provided comments. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This study was approved by the Queens University Belfast ethics committee (QUB-BS-AREC-19-004) and Belfast Zoo.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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